Sustainability of an Ecological Treatment System Evaluated with Emergy

The Waterman Ecological Treatment System (WETS)

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Abstract

Agricultural waste management is a difficult challenge facing animal producers. New technologies are needed to address problems such as increasing costs, stronger environmental standards, and negative social perceptions of agricultural waste management. Conventional methods of animal waste treatment lead to undesirable odors and contamination of local waters. As urban society encroaches on the rural landscape, on-site treatment of animal wastes, rather than current dilution and land application, will become increasingly important. New technologies must be sustainable and cost-effective to address the needs of animal producers.

Wetlands and other ecological treatment systems (ETS) offer waste treatment solutions that use renewable energy and natural processes to metabolize wastes and provide valuable products in addition to purified water. The goal of this study was to quantify and compare the sustainability and resource use of an ETS with other waste treatment technologies. This study compares an ETS treating liquid manure to Italian, Swedish, and Mexican waste treatment systems. Emergy analysis was used for this comparison to provide a holistic metric to evaluate the sustainability, resource use and environmental impact of an ETS. Emergy quantifies system inputs and outputs on a common basis. The benefit of this is that a diverse array of flows can be compared on an equal basis.

The Waterman Ecological Treatment System (WETS) analyzed in this study was 75% more sustainable than conventional municipal waste water treatment plants because the WETS relies more on natural processes, rather than chemical and mechanical inputs, to treat waste water. Three factors contributed to more emergy input per gram of treated water required for waste treatment by the WETS when compared with other systems: the WETS is a research facility that is not optimized for efficiency, the WETS is treating high strength animal waste, and the WETS is not treating its maximum capacity for waste.

Results from the emergy analysis show that sustainability of the WETS can be improved by reducing the electricity inputs and increasing the volume of waste treated. Sensitivity analyses revealed that increasing the quantity of waste treated by the system to the design treatment capacity would improve the sustainability of the system by

400%. These results demonstrate potential for ETS to provide sustainable solutions to agricultural waste treatment problems.

Keywords: Emergy, Sustainability, Ecological Waste Treatment

Introduction

The Waterman Ecological Treatment System (WETS) is a research facility that is part of Waterman Farm at The Ohio State University on the northwest corner of the Columbus campus at 2433 Carmack Road. The system is housed in a 9 by 12 meter greenhouse. The WETS is composed of a multi-cellular design that provides the satisfactorily treats the dairy wash water from the adjacent dairy facility on Waterman farm (Figure 1). Each of the four replicated treatment lines contains anaerobic, anoxic, closed aerobic, and vegetated aerobic reactors. This series of tanks is followed by a clarifier tank that has a feedback loop to the first anaerobic tank and also feeds into a wetland. Following the wetland are two vegetated aerobic tanks and another clarifier with a feedback loop into the first aerobic tank in the second series. The second clarifier feeds into two wetland tanks (Figure 1). Because the WETS relies on metabolic processes supported by solar energy it was necessary to use an evaluation method that could account for renewable inputs. Renewable resources, such as sunlight, are often not accounted for in traditional economic or energy analyses. Additionally, other traditional methods of analysis do not capture the entire upstream system of inputs that are required to make a product or service and therefore do not fully measure environmental impact. Emergy analysis is a holistic evaluation tool that provides a metric that measures environmental impact by accounting for renewable and non-renewable system inputs on a common basis.

Because of these advantages emergy analysis was used to assess the sustainability of the WETS and quantify all the environmental and purchased inputs on a common scale. Emergy analysis measures all economic and environmental inputs to each product or service as solar energy equivalents (Ulgiati, 1997). The units for solar energy are solar emjoules (sej). Raw data units (g, J, $, or hrs) are converted to solar emjoules by solar transformities. The solar transformity accounts for the amount of solar energy required to make one unit of a product. For example, tomatoes require direct sun energy as well as other inputs such as fertilizer, pesticides and labor that can be translated into units of solar energy. This total solar energy needed to create the tomatoes can be divided by the mass of the yield to create a transformity. If 200,000 solar emjoules were used to produce a vine of tomatoes (approximately 2,000 grams), the solar transformity for the vine of tomatoes would be 100 sej per gram of tomato. "Transformity is also an indirect measure of how much activity of the environment, either directly or indirectly, has been required to manufacture a given product" (Brown 1997).

Results from the WETS analysis were compared to past emergy analyses of waste water treatment operations. These included a municipal waste water treatment system (Bastianioni, 2003), a Swedish conventional waste water treatment plant (CWWTP), a Swedish constructed wetland combined with a conventional treatment plant, a large-scale micro algae treatment plant (Grönlund, 2004), a Mexican constructed wetland, and a Mexican package plant (Nelson, 2001). It was expected that the WETS was more sustainable and had less of an environmental load than conventional methods of waste treatment, but required more emergy per gram of treated water as it is a research facility

Methods

Figure 2 illustrates the inputs and interactions within the WETS that are required to produce the yields of plant biomass and clean water. Renewable inputs are located on the left border of the diagram. Non-renewable and purchased inputs are located along the upper portion of the diagram. The dairy waste enters the system and is diluted with ground water. This mixture interacts with plants, microbes, and the structures in the greenhouse to yield the products of harvested biomass and clean water. This main interaction also yields sludge which is recycled from the clarifiers to the anaerobic tank. Normally, sludge is removed from such systems, but because of the recycle loop and high rate of digestion of solids in the WETS, none was removed during the first year of operation. Most purchased and non-renewable inputs are part of the structure of the greenhouse. Labor inputs are shown to interact with the greenhouse for construction and with the plants for annual harvesting.

The system diagram aided in the construction of the emergy analysis table (Table 1) by providing a visual representation and organization of the entire system of study. All lines in the system diagram that cross the boundary were inputs to the system that appear in the emergy analysis table (Odum, 1996). In an emergy analysis table all renewable inputs appear at the top of the table and non-renewable purchased inputs below. For each input, data were organized into columns labeled inputs, data units ($, g, J, hrs), transformity (sej/unit), solar emergy (sej/time period), and reference. Solar emergy was totaled for the whole system (Y) and indices (Table 2) are calculated based upon total renewable (R), local non-renewable (N) and purchased resources (P) (Figure 3). Ratios and indices were calculated to facilitate the comparison of various systems or products. Ratios and indices of importance for this paper are the Emergy Yield Ratio (EYR), Environmental Loading Ratio (ELR) and Sustainability Index (SI) (Brown, 1997). The EYR was calculated by dividing the total emergy of the system (Y) by the emergy of purchased inputs and is an indicator of the systems use of purchased resources. The ELR was calculated by dividing the purchased emergy by the renewable emergy and is an indicator of ecosystem stress due to production or resource consumption activity. The Sustainability Index is a ratio of EYR to ELR and incorporates measures of dependence on non-renewable resources, system yield, and environmental loading to clearly evaluate the impact and sustainability of the system.

Derived from the emergy analysis table is another beneficial analytical tool, the emergy signature diagram. Total emergy per time period (the third data column) for each system input is graphed in order of increasing transformity. This visual representation of the data aids in selecting the inputs with the greatest emergy for further analysis of data accuracy and sensitivity analysis for system improvements.

Results

From the emergy signature diagram (Figure 4), it is clear that electricity, gravel, and labor are the inputs into the WETS with the greatest amount of emergy. The renewable input with the greatest emergy is dairy manure. The emergy analysis reveals a total emergy consumption of 5.95×10^{15} solar emjoules per year (Tables 1 & 2). The total emergy is divided between renewable resources (R) and purchased resources (P).

Renewable and purchased resources for the system totaled $5.34x10^{13}$ sej/yr and $5.90x10^{15}$ sej/yr respectively with 0.9% from renewable and the remaining 99.1% from purchased resources. The resulting EYR is 1.01 and the ELR is 110. The overall system sustainability or sustainability index is $9.13x10^{-3}$.

Sensitivity analyses (Figures 5 & 6) demonstrated the potential for the sustainability index to increase from $9.13x10^{-3}$ (current) to $4.73x10^{-2}$ if the amount of waste the system treated was increased from 1,350 to 7,500 liters per day. Figure 7 showed a decrease in transformity from $2.53x10^{7}$ (current) to less than $5.0x10^{6}$ sej/g as the system increased the amount of treated waste to its maximum capacity of 7,500 liters. The WETS in its current state requires more emergy per joule of treated water than the other waste treatment systems with a transformity of $1.24x10^{8}$ versus $3.46x10^{6}$ for the Italian municipal waste water treatment plant (Bastianoni, 2003), $3.76x10^{6}$ sej/J for the Swedish municipal waste water treatment systems (Grönlund, 2004) and $6.85x10^{6}$ sej/J for the Mexican constructed wetlands and $4.83x10^{6}$ sej/J for the Mexican Package Plant both treating residential waste water(Nelson, 2001).

Discussion

Assumptions

As with any complex analysis, assumptions were required to complete the study. The project life for this analysis was assumed to be 10 years. The system was assumed to operate for 9 months each year. Actual annual operation varies from year-to-year depending on the weather because the greenhouse is currently not heated. An important assumption is that the dairy waste treated in this system is a renewable resource. Nelson (2001) states that wastewater “is a potentially valuable renewable natural resource, containing valuable nutrients and water which can be used to construct and support productive wetland ecosystems”. While it is possible to argue that a product of modern intensive milk production is not renewable because of the intensity of the external inputs, the dairy waste is a free resource to the system of study and was assumed to be consistently available during the 10-year project life.

Limitations

From the Emergy Signature Diagram (Figure 4) it is apparent that the largest purchased input of emergy was electricity, and the largest renewable input of emergy was dairy waste. Assigning a transformity to the dairy waste (Bastianoni, 2000) was problematic because very few transformities for similar material were available. While a value was found from a Puerto Rican dairy farm, the system was not described in enough detail to know if the system was similar to the Waterman Dairy. General comparisons or estimations cannot be made between the Puerto Rican system and the Waterman Dairy Farm. However, due to a lack of similar studies the transformity for dairy manure from the Puerto Rican farm will have to be used. The importance of the value used for the waste transformity was demonstrated with a sensitivity analysis (Tables 5 & 6). Doubling or halving the transformity doubled or halved the Percent Renewable and Sustainability Index because of the magnitude of emergy in the dairy waste relative to the other renewable inputs.

A limitation of this study was the type of system comparison. The other systems in Sweden, Italy, and Mexico do not treat dairy waste, but waste water from municipalities. Dairy waste has higher nutrient concentrations than municipal sources and is likely to result in a higher transformity for water treated by the WETS. More useful comparisons would analyze the current dairy manure waste management practices and compare them to the sustainability of the WETS. The lack of prior analyses precluded relevant comparisons with similar systems. Emergy analyses in the area of conventional dairy manure treatment would enhance the comparative scope of this paper. It can be predicted that conventional treatment of dairy waste is less sustainable than an ETS based on results from the conventional system treating municipal waste water.

Analysis

The Sustainability Indices (Table 4) of the systems in this study ranged from 2.4×10^{-4} for the Swedish (CWWTP) and 5.7×10^{-2} for the large scale Swedish Algal treatment plant. Sustainability indices were not calculated for the Mexican systems due to a lack of data. Currently, the WETS has a Sustainability Index of 9.13×10^{-3} and is more sustainable than both Swedish CWWTP and the Swedish treatment plant with the constructed wetland. Figure 5 shows the sensitivity of treating additional dairy waste on the Sustainability Index of the WETS. As more waste is treated, the Sustainability Index linearly increases. This is true because more emergy is being dissipated by the system with the same purchased inputs. Near the peak designed capacity for the WETS the sustainability index is similar to that of the Swedish Algal treatment plant (Table 4) and moves beyond the optimized conventional treatment plants of Italy and Sweden.

Nelson (2001), calculated a transformity of 6.86×10^{6} sej/J for treating residential waste water for 40 people with a constructed wetland. This treatment system reflects a value closer to that of an optimized ETS. A package plant treating waste for 40 people had a transformity of 4.83×10^{6} sej/J, similar to that of the other CWWTP systems presented in this paper. Nelson (2001) attributes the higher transformities of the constructed wetland to reduced water discharges from the system as it is used to support the wetland ecosystem (2001). Figure 7 shows the impact of increasing the amount of manure treated by the WETS on the transformity for clean water. At maximum capacity, the WETS has a transformity for treated water of 2.36×10^{7} sej/J. Currently, the WETS has 4 replicate lines for research purposes, while an operational system would be designed with two larger or even one single treatment line in the same amount of space to treat more water per area. If the WETS were a fully optimized system designed for maximum capacity, not as a research facility, the system performance could be comparable or exceed the other waste water treatment methods compared in Tables 3 & 4. In addition to having reduced discharges compared to conventional systems, the WETS is treating a waste source that is much “stronger” and contains more emergy than municipal waste, thus requiring to a larger amount of emergy per unit of waste treated.

A sensitivity analysis of the percentage of reduction of electricity was done in order to understand the possibility of using more efficient equipment if a new system were designed and built. From Figure 6, it was surprising to find that reductions in electricity do not have a large impact on the Sustainability Index relative to the impact of increasing the amount of waste treated by the system. Purchased inputs would have to be reduced by 80% in order to have the same impact on the Sustainability Index. This can be explained by the relatively large quantity and transformity of other purchased inputs relative to renewable inputs.

Future Work

An area of improvement for the WETS would be to increase annual treatment time to include the cold winter months. An Emergy Benefit/Cost analysis would be necessary to verify if the additional heating requirements would be offset by the value of treating additional waste. Energy and heat sources can be derived from renewable sources like solar panels and wind energy. Additionally, potential exists to use methane for a heating source or an anaerobic digester to produce electricity. The Sustainability Index would be the indicator for the optimal combination of additional heating and energy sources to allow the WETS to function throughout the cold season.

In order to improve the use of ETS in agricultural applications, design characteristics for various sized dairy farms need to be determined. Ranges of cattle can be established to optimally size an ETS for specific farms. Establishing treatment capacities will further the possibility of large scale utilization of sustainable waste treatment for dairy farms.

Conclusion

It has been found that the WETS is more sustainable than conventional waste water treatment plants. The WETS can be further optimized beyond the research configuration to improve its use of purchased non-renewable resources by increasing the amount of treated dairy waste. This would improve the Sustainability Index from 9.13×10^{-3} to 4.73×10^{-2}, making it comparable to the large scale algae treatment facility in Sweden. Electricity is the input with the greatest emergy in the system and cannot be realistically reduced to have a significant impact on the sustainability of the system due to the magnitude of other purchased inputs. Future ETS should be designed and operated to treat a level of waste near their maximum capacity. This would make efficient use of purchased inputs to treat large quantities of waste. ETS can also maximize their treatment capacity by increasing annual treatment time to include cold winter months. If this is done without increasing operating emergy inputs, such as would be the case with methane collected from the anaerobic digesters, this could result in large gains in sustainability.

Dairy manure management with an ETS is no longer a stigma to society as ETS offer on-site, efficient *treatment* of waste instead of waste disposal alternatives. With emergy it has been shown that the WETS can be modified and improved to be as sustainable as large scale treatment systems. The WETS is a good example of a sustainable waste treatment method that solves many difficult problems associated with dairy waste management.

Appendix

Figures and Tables

Figure 1 - Cellular layout of the Waterman Ecological Waste Treatment System

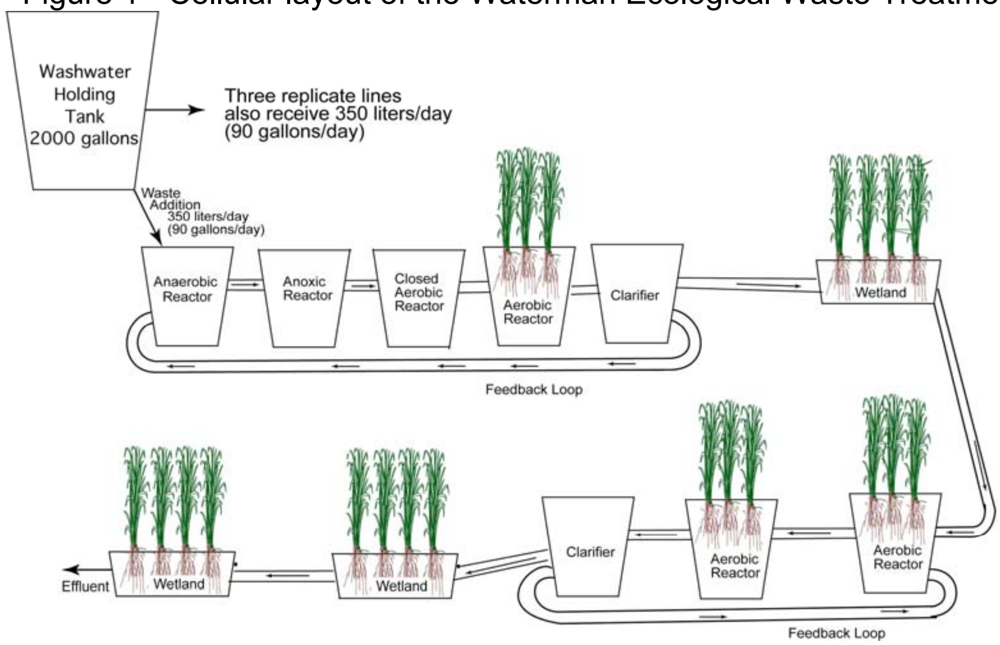

Figure 2 – Complete systems diagram of the Waterman Greenhouse

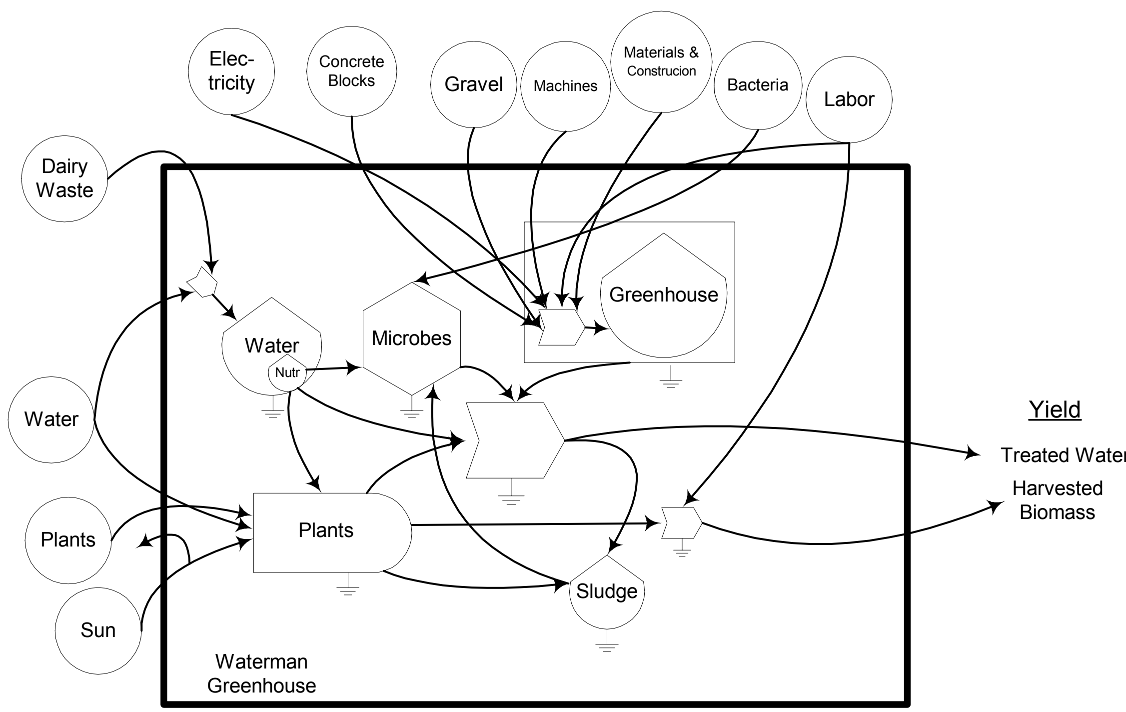

Figure 3 – Aggregated diagram with annual emergy flows

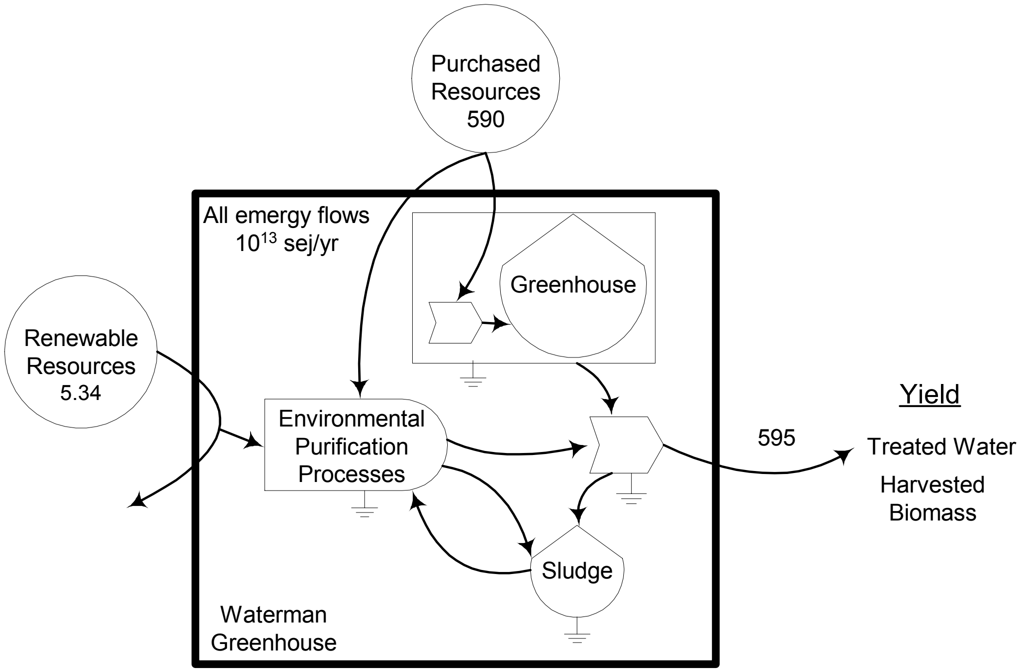

Figure 4 – Emergy signature diagram for the WETS inputs

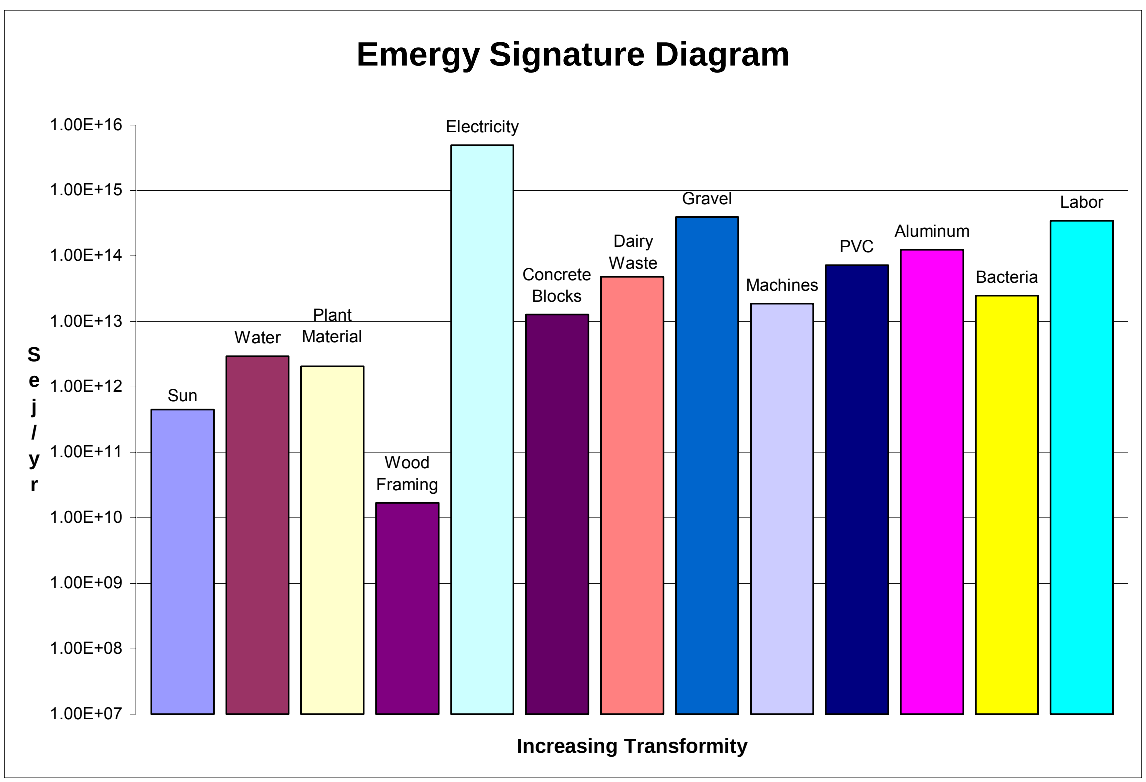

Figure 5 – Sensitivity of sustainability varied by amount of treated waste

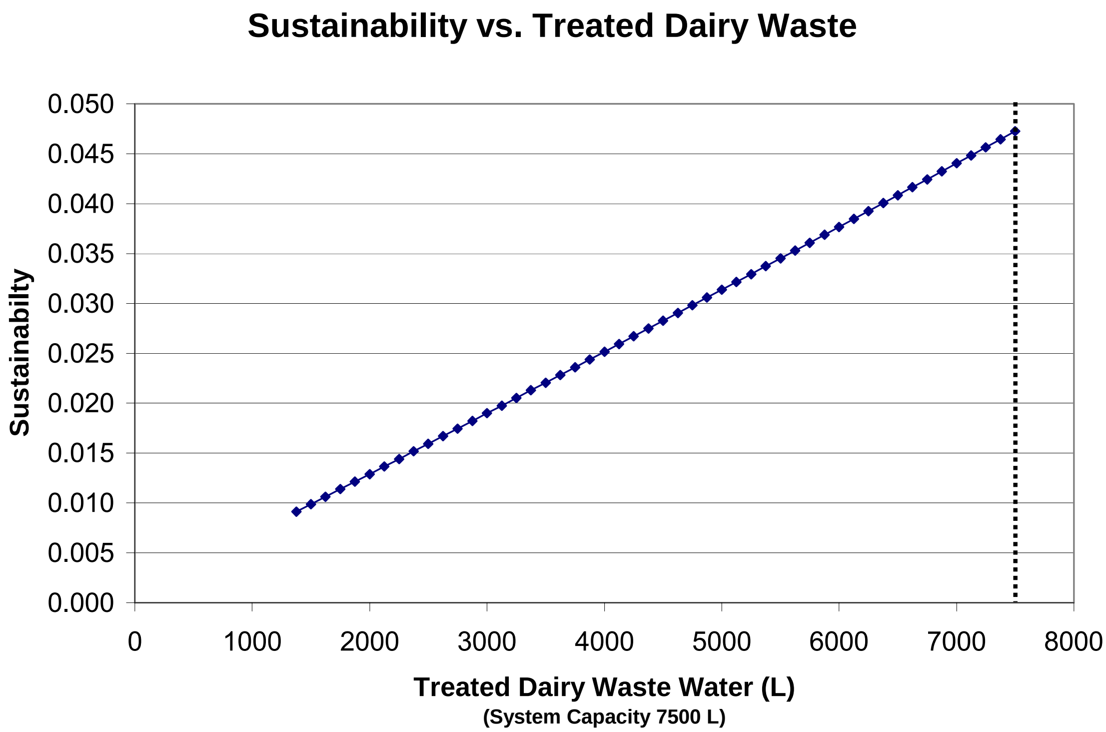

Figure 6 – Sensitivity of sustainability with reductions of electricity usage

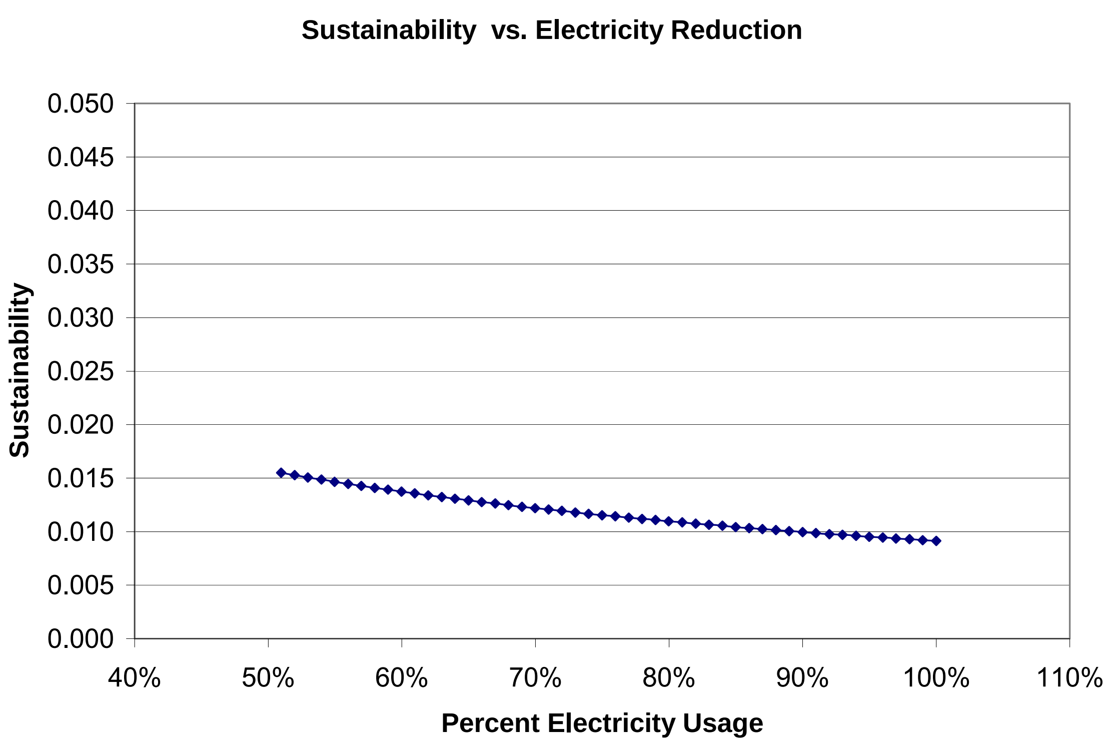

Figure 7 – Sensitivity of clean water transformity varied by amount of treated waste

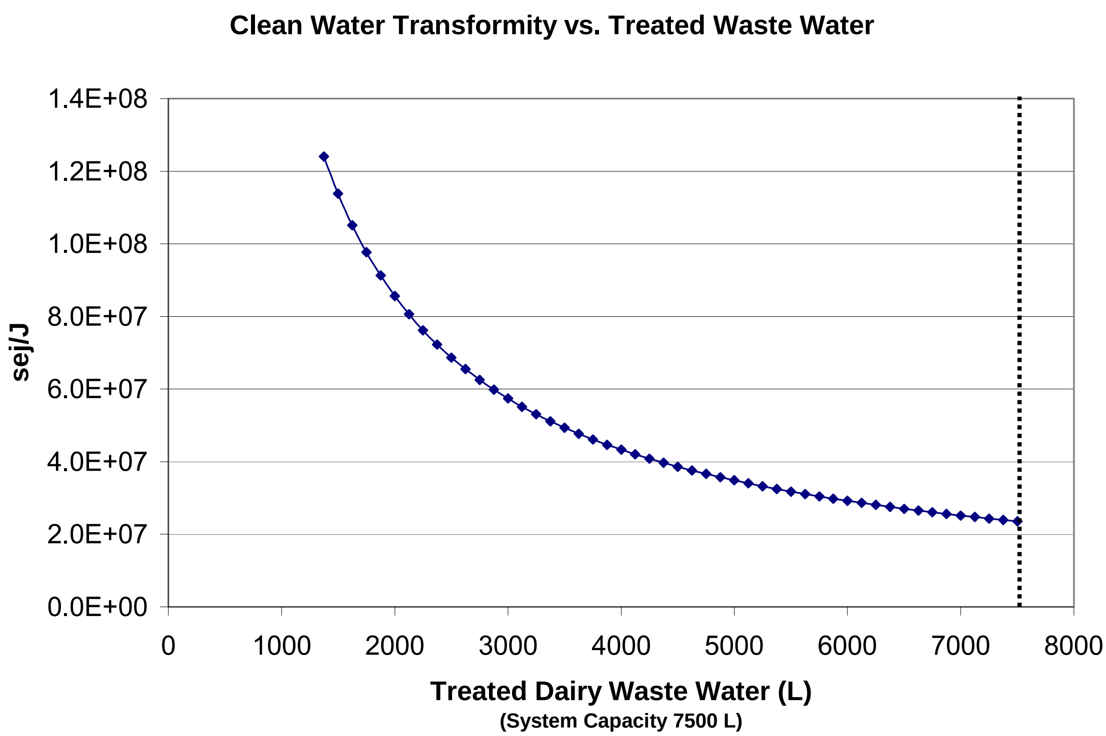

Table 1 – Emergy analysis table from systems diagrams in Figs 2 & 3

Item	Data Units (J, g, hrs, $)	Emergy/unit (sej/unit)	Solar Emergy (sej/yr)	Reference
Inputs:				
Renewable resources				
1. Sun, J	4.54E+11	1.00E+00	4.54E+11	www.nasa.gov
2. Water, J	7.16E+07	4.10E+04	2.94E+12	Brown et al., 1995
3. Plant Material, g	1.40E+04	1.00E+04	2.06E+12	Odum, 1996
4. Dairy Waste, g	4.24E+05	1.13E+08	4.79E+13	Bastianoni, 2000
Total Renewable Emergy			5.34E+13	
Purchased resources				
5. Concrete Blocks, g	1.83E+05	7.00E+07	1.28E+13	Brown et al., 1996
6. Gravel, g	3.03E+05	1.30E+09	3.94E+14	Campbell, 2004
7. Machines, g	4.54E+03	4.10E+09	1.86E+13	Buranakarn, 1998
8. Electricity, J	3.07E+10	1.60E+05	4.91E+15	Odum, 1996
9. Bacteria, $	3.82E+01	6.54E+11	2.50E+13	Odum, 1996
10. Wood Frame, J	9.03E+05	1.88E+04	1.69E+10	Lefroy, 2003
11. PVC, g	1.23E+04	5.85E+09	7.21E+13	Buranakarn, 1998
12. Aluminum, g	9.94E+03	1.25E+10	1.25E+14	Buranakarn, 1998
13. Total Labor, hr	6.00E+01		3.47E+14	http://www.unicamp.br/
University Professor	5.00E+00	2.20E+13	1.10E+14	
Agricultural Technician	5.50E+01	4.30E+12	2.37E+14	
Total Non-Renewable Emergy			5.90E+15	
Total Emergy			5.95E+15	
Yield				
14. Clean Water, g	2.35E+08	2.53E+07	5.95E+15	
15. Harvested Biomass, g	4.76E+04	1.25E+11	5.95E+15	

Table 2 – Ratios and Indices calculated for WETS

Percent Renewable	R/(R+P)	0.90%
Emergy Yield Ratio (EYR)	Y/P	1.01
Environmental Loading Ratio (ELR)	P/R	110.56
Sustainability Index (SI)	EYR/ELR	0.00913

Table 3 –Transformity comparisons

Transformity of Treated Water (sej/J)	
WETS	1.24E+08
Italian WWTP	3.46E+06
Swedish WWTP	3.76E+06
Mexican Constr. Wetland	6.85E+06
Mexican Package Plant	4.83E+06

Table 4 – Sustainability comparisons

Sustainability Indices	
WETS	0.00913
Swedish WWTP	0.00024
Swedish TP + Constr. Wetland	0.00520
Swedish Algal	0.05700

Table 5 – Manure transformity doubled

Percent Renewable	R/(R+P)	1.69%
Emergy Yield Ratio (EYR)	Y/P	1.02
Environmental Loading Ratio (ELR)	P/R	58.25
Sustainability Index (SI)	EYR/ELR	0.01746

Table 6 – Manure transformity halved

Percent Renewable	R/(R+P)	0.50%
Emergy Yield Ratio (EYR)	Y/P	1.00
Environmental Loading Ratio (ELR)	P/R	200.64
Sustainability Index (SI)	EYR/ELR	0.00501

Calculations

Renewable resources

1. *Solar energy*
Total greenhouse area: 110 m^2
Insolation: 4.75 x 10^9 J/m^2 (http://eosweb.larc.nasa.gov/)
Albedo: 13% (http://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?uid=3030)
Annual Solar Energy: 110 m^2 x 4.75x10^9 J/m^2 x (1-0.13) = 4.54x10^{11} J
Transformity: 1.0 sej/J (by definition)

2. *Groundwater energy*
Total Volume of System: 14.61 m^3
Density of groundwater: 1x10^6 g/m^3
Energy in ground water: 4.9 J/g (Buenfil, 2001)
System water energy: 14.61 m^3 x 1x10^6 g/m^3 x 4.9 J/g = 7.16x10^7 J
Transformity: 4.10×10^4 sej/J (Brown et al., 1995)

3. *Plant Material*
System Harvest Biomass: 23,412 g/yr
Estimated Initial Biomass: 23, 412 g x 0.40 = 9,365 g
Transformity: 1.00x10^4 sej/g (Odum, 1996)

4. *Dairy Waste*
Treated Volume of Water: 1375 L/day = 378,125 L/yr
Total Suspended Solids: 1.121 g/L
Total Annual Treated Manure: 378,125 L/yr x 1.121 g/L = 4.24x10^5 g
Manure Transformity (Puerto Rican dairy): 1.13 x 10^8 sej/g (Bastianoni, 2000)

Purchased resources

5. *Concrete Blocks*
Project life: 10 years
Blocks per treatment line: ~35
Weight: ~30 lbs
Weight: (435.59 g/lb x 30 lbs x 35 x 4)/10 = $1.83x10^5$ g
Transformity: $7x10^7$ sej/g (Brown and McClanahan, 1996)

6. *Gravel*
Project Life: 10 years
Total gravel volume: 1,990,914 cm^3
Density of loose, dry gravel: 1.522 g/cm^3
Weight of gravel: (1,990, 914 x 1.522)/10 = $3.03x10^5$ g
Transformity: $1.3x10^9$ sej/g (Campbell, 2004)

7. *Machines*
Project Life: 10 years
Weight of machinery: ~100 lbs
Weight conversion: 435.59 g/lb
Total Weight: (100 x 435.59)/10 = $4.54x10^3$ g
Transformity: $4.10x10^9$ sej/g (Buranakarn, 1998)

8. *Electricity*
Air Pump Energy Consumption (9 months/year): 803 kWh x 9 = 7227 kWh
Fan Energy Consumption: E = 0.746 (kW/HP) x HP x LF x hrs x (100 / Eff)
= 0.746 x 1/3 x 0.25 x 1800 x (100/0.90) = 12,433 kWh
Total Annual Electricity Consumption: Air Pump + 2 Fans = 32,093 kWh
1 kWh = $3.6x10^6$ J → 32,093 kWh x $3.6x10^6$ J/kWh = $1.16x10^{11}$ J
Transformity: $1.60x10^5$ sej/J (Odum, 1996)

9. *Bacteria*
Cost of Bacteria: $38.15
Transformity: $6.54x10^{11}$ sej/$ (Odum, 1996)

10. *Wood Frame*
Project Life: 10 years
Board feet: 300
Density of oak lumber: 750 kg/m^3
Wood energy: (300 x 0.0023597 m^3 x 750 kg/m^3 x 2.2 lb/kg x 7.33 x 1055)/10 =
$9.03x10^5$ J
Transformity: $1.88x10^4$ sej/J (Lefroy, 2003)

11. *PVC*
Project Life: 10 years
Total PVC Weight: 123,175 g
Transformity: $5.85x10^9$ (Buranakarn, 1998)

12. *Aluminum*
Project Life: 10 years
Length of Tubing: 840 ft
Linear density of 1.5” tubing: 0.266 lb/ft
Weight of aluminum: 840 ft x 0.266 lb/ft x 453.59g/lb = $9.94x10^3$ g
Transformity: $1.25x10^{10}$ (Buranakarn, 1998)

13. *Labor*
Project Life: 10 years
University professor: 50 hours
Transformity: $2.20x10^{13}$ sej/hr (http://www.unicamp.br/)
Agricultural Technicians: 450 hours
Transformity: $4.30x10^{12}$ sej/hr (http://www.unicamp.br/)

Yield

14. *Clean Water*
Quantity of Water Treated: $2.35x10^8$ g
Total required emergy: $5.95x10^{15}$ sej
Transformity: $2.53x10^7$ sej/g (Sikdar, 2005)

15. *Harvested Biomass*
Quantity of Biomass Harvested: $4.76x10^4$ g
Total required emergy: $5.95x10^{15}$ sej/g
Transformity: $1.25x10^{11}$ sej

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